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Updated failure rates and risk management in process industries

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Abstract

In process industries more and more decisions are "risk based", such as equipment inspection, maintenance and management of change. Risk assessment is, in turn, based on the "Failure Rates". For process plants, where Major Accident Hazard Legislation is enforced, even competent authorities' decisions, such as licensing and land use planning LUP, are "risk based" and, consequently, driven by Failure Rates. The Failure Rates currently in use for process equipment derive, basically from , a few large systematic studies conducted in the Sixties and Seventies on failure frequencies and modes. Many new materials, new production and management methods have been introduced and their effects on aging mechanisms on a large scale are still unknown. A few major multinational companies have proprietary failure databases, which are supposed to be up to date, both most companies, as well as Authorities, have to trust in public domain Failure Rates, which are poor and generic and could drive to questionable decisions. A few European Competent Authorities are trying to face the problem, by stating a set of trusted Failure Rates, suitable just for LUP. INAIL, as in charge for pressure equipment control throughout Italy, is gathering data for updating generic failure frequencies. The project is aiming to provide a sound knowledge base about pressure equipment failure rates and modes, in order to support the Risk Management by both industry and Authorities.

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Keywords. Pressure Equipment, Failure Modes, Major Accident Hazard, Risk Based Decision.

1. Introduction

In the process industries, such as oil, gas, petrochemical, chemical and power, reliability data include equipment failure modes and frequencies, which are essential to ensure system availability and production continuity. These data become even more important at the plants, where is applied the Seveso Directive for the control of Major Accident Hazard, which requires an integrated view of all safety related issues. In Seveso establishments, the

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detailed knowledge of the equipment reliability is the keystones for and effective risk assessment and management. Failure rates, in particular, are essential for the probabilistic safety assessment, as required by Seveso Directive. Furthermore this data is essential also to implement a risk based program of inspection and possibly of maintenance, aiming at optimizing safety, performances and costs. In chapter 1, both risk assessment and risk management are discussed, focusing the importance of the pressure equipment reliability. In chapter 2 the importance of failure rates for an efficient risk management is discussed. Chapter 3 discusses the efforts for providing trustable set of failure to the process industries. The fourth chapter presents preliminary results about a number of pressure equipment failures. The last chapter discusses the potential of an improved understanding of reliability matter for increase safety industries.

2. Failure Rates and Risk Management in the common practice of process industries

The Generic Failure Rates are derived by the statistical analysis of the failure frequency, as recorded in experimental campaigns. The scope of experimental campaigns may be sector based, national or international. Likelihood of failure LoF derives from Generic Failure Rates combined with specific factors. In this way, the Failure Rates are essential for risk assessment and management in any process industries. At Seveso establishments they are even more important, due to the specific legal duties. To avoid ambiguities the Directive 2012/18/EU (Seveso III) on the control of major-accident hazards at industrial establishment is referred. It will replace the previous Directive 96/82/CE (Seveso II) in all European Union, before July 2015.

2.1. Plants under "Seveso" Legislation

According to the art. 10 of the Directive 2012/18/EU Seveso III operators of concerned establishments are required every five years to provide an up-to-date "Safety Report" to the Competent Authorities. From the assessment of the Safety Report descend important decisions, including the authorization of new plants, the prescription of plant modifications, the core of the safety report is a quantitative, or possibly, semi-quantitative analysis of risks, carried out by the operator, or rather by a few advisers and consultants. Given the importance of the decisions arising from the evaluation of the risk, it is important to analyze in detail the practice usually adopted.

The common practice of the risk analysis has three steps:

- 1) identification of the TOP-EVENTs (accidents with major consequences) by means of the HAZOP method;
- 2) calculation, for each TOP-EVENT, of its occurrence probability, by means of Fault Three and Event tree analysis, FT/ETA, which are based on the reliability of the preventive and protective systems, derived, in turn, by the Failure Rates of the mechanical, hydraulic, electrical, electronic and possibly human and organizational systems, aiming at preventing or protecting from the release of hazardous materials;
- 3) calculation, for each event with a significant probability, of the damage areas, by means of physical models. scenarios with lethal, irreversible and reversible consequences are considered, as well as damages to property and environment and possibly domino effects. Consequences within or outside the establishment's fences are discriminated.

The probabilistic evaluations coupled with consequence modeling and potential impact area computation are essential for Authorities to make vital decisions about new plants approval, emergency planning (including resource allocation) and land use planning LUP. Also the identification of critical system within hazardous plants is driven by the failure rates, which, in such a way, affect also the safety management procedures. In a few countries, as France. Germany and Italy, the compatibility criteria rely more on the severity of the possible "consequences". The probability enters as a filter for the scenarios and related damage areas to be included (typically > 10^{-6}). In other countries, such as Netherlands or UK, the decisions are driven by the calculation of the Societal Risk, which involve calculating the probability of casualties at a given exposure [1]. This calculation depend also on event probability, which in turn depend on Failure Rates. In both cases general failure rates drive decisions, but in the consequence based method the error propagation could be even higher than in Societal Risk approach, as likelihood becomes an absolute filter. The scientific weakness of the generic failure frequencies have been discussed by a historical review of Fragola [2]. Authorities must anyway accept a trade-off to make standardized and uniform decisions. An inadequate value of a single Failure Rate value in the fault tree is able to affect vital decisions. Recent innovations are increasing component reliability but if the authorities accept arbitrary extrapolations of Failure Rates, could make imprudent decisions, excluding possible catastrophic events. A conservative approach is preferable for the Authorities' decisions. The Buncefield incident has demonstrated the importance of an accurate assessment of the risk of involvement in the area of industrial accidents and the criticality of the general frequency of fault, for which the final report on the "lessons learned" complains a level of trust too low [3]. Following this report, an initial feasibility study on upgrading generic fault rate, aiming to improve the decision-making process was promoted by the British authorities [4].

According to the art. 20 of the Seveso III Directive, the Competent Authorities organizes periodical Inspections at hazardous establishments. They must be sufficient for a planned and systematic examination of the systems being employed at the establishment, whether of a technical, organizational or managerial nature, so as to ensure in particular their adequateness to prevent (or mitigate) accident events. A way to make effective inspection, is to concentrate the efforts on the system, recognized as critical for accident prevention and protection. For technical system it is essential to trust in credible failures frequencies, to individuate the actual critical systems.

2.2. Other plants (non Seveso)

The potential of RBI Risk Based Inspection for optimizing Inspection planning at process plants has been widely discussed in many recent papers [5]. The basic idea of RBI is the optimization of inspection intervals, instead of fixed frequencies, required by traditional time based approach. In RBI, inspection times and modes are affected by an adequate assessment of failure risk, assumed as the combination of LoF and Severity of Consequences, as well as by the tolerable risk level and by the results of previous inspections. To calculate the LoF, the generic Failure Rates are modified, according to the knowledge of the materials and of the operation condition. RBI is accepted in many European Countries also for planning mandatory equipment verifications. In Italy, for a few critical types of equipment, including fired and unfired pressure equipment, the inspection interval is fixed by law; but exceptions are possible, if the RBI implementation is demonstrated adequate to reduce the risk level lower than fixed periodical inspection. RBI is good for Seveso establishments, as the results of mandatory audits on human and organizational factors may be exploited to improve LoF, as demonstrated by Bragatto & al. [6]. Anyway RBI may be adequately applied at other process plants, where equipment availability and operation continuity are critical issues. More generally speaking, using the ISO 31000 definitions, the risk management in a process establishment is aimed to understand and control uncertainties in the objective of a process plant, which is basically a profitable and safe production. Equipment failure is still a major uncertainty in a process plant and consequently efforts to develop knowledge about the frequency and the mode of equipment failures are worthwhile. For that reason a credible set of generic failure rates is essential to promote an efficient risk management even at small and medium sized process plants as discussed by Bragatto & al. [7]

3. "Failure Rates" in process industries: from the Seventies to the present

As discussed in previous chapter, in all process industries the probabilistic assessment is essential for both risk assessment and risk management. At the very basis of the complex architecture there are always the failure rate, both for equipment, instruments and humans. The present paper focuses just mechanical failures on pressure equipment. For pressure vessels, it is less difficult to gather data, because almost all phases of their life-cycle are driven by national regulations. Instrument failures and human errors are equally important; but they are not subject to strict regulations and data collection is more difficult. The story of the Failure Rates for pressure equipment starts many years ago and it is essential to be understood, in order to identify the weakness of the present approach to define the road for an effective improvement.

3.1. The beginning

Since the early 70's a huge effort was made to provide the nuclear and chemical engineers with a credible set of reliability data of pressure vessels. In an article by Bush [8], the historical studies, conducted in previous decades at three major industrial countries, USA, UK and Germany, are reviewed and compared in a critical way. In the review eight national studies on pressure vessels are reported in detail. In each study, 10.000 to 100.000 pieces of equipment were observed for ten years and more. Those studies consider, as a whole, 3 million years-vessel (both fired and unfired) with some 8.600 minor faults and 155 major events. The average historical rates, as elaborated by Bragatto & al. [9], are shown in table 1.

Table 1 The average historical rates, coming from a few campaigns in the 60's and 70's.

	minor	major failures
Average F.R. (y-1)	3,9 10-4	2,6 10-5.
Quad. dev.	18%	88% .

In the early 80's, the first scientific LUP studies were presented for the areas of Canvey Island UK and Rijmond in NL [9-10]. The two studies proposed two sets of failure frequencies. Both failure rates sets have been derived from large historical datasets, handled by a number of experts, which customized them for process industries. Thereafter for many years, they was used trusted in Europe, due to the lack of alternatives.

Since the 90s, two things occurred that completely changed the industry: quality management, which has been completely revolutionized by ISO 9000, and the management of the certification that has been completely revolutionized by the PED Directive. Furthermore, plants are aging more and more, due to poor investments; the "new" materials, introduced in the 70's and 80's are not well known on a large scale. Also acceptance criteria for in-service inspections are critical for ageing equipment. For all these reason, it's essential to update the recognized national and international information sources for the failure rates, in particular for the pressure equipment.

3.2. Further European Experiences

The quality of the data on equipment failures used in process industries should be updated to promote a more effective use in risk management, both for companies and authorities. As in most European countries, LUP decisions are based on event probability, for over a decade, there has been a commitment of the Competent Authorities to provide shared failure rates. The main sources are the following:

- The "PURPLE BOOK" is a study ordered by the Dutch Competent Authority to the TNO [1]. The values of frequencies are the result of discussions between representatives of the competent authorities and the government. The frequencies are often based on old data available at that time, in combination with expert judgment [12].
- FRED (UK) is managed by HSE, the British Competent Authority [13]. The method is similar to that of the Purple Book, i.e. processing of consolidated data and expert judgment. The study, however, is more recent and the approach is much more conservative, thus the failure rates are systematically higher.
- AMINAL (BE), the study AMINAL from Belgium is recent [14]. It is not far from the Purple Book, although data are presented in a different format.
- American Petroleum Institute API (US) Even though it is a private body, API is highly influencing the Oil & Gas industry. The general failure rates are provided for many types of equipment, in the frame work of the resources to be used to implement a Risk Based Inspection (RBI) program [15].

A very recent HSE study [16] is trying an innovative path, to consider as a valuable information source the major accident records, which, by the Seveso Directive, must be reported to the Competent Authorities. The difficulty is figuring out which is the reference population, because there are no data on the total number of pipes and pressure vessels at the Seveso establishments [17]. The proposal to exploit Google Earth is applicable just for external pipelines, not for establishments. Furthermore, only the catastrophic failures can be considered. The National Archives of fatalities could be a further source of data, but just faults with fatal consequences may be studied. That is misleading because there are many major failures with severe economic and environmental consequences, but without injuries.

Large multinational companies are able to turn around the weakness of generic Failure Rates in public domain, as they control directly hundreds of plants, with thousands of pressure items, which may be a significant reference population for any statistical studies. These Studies, unfortunately, are proprietary and cannot be found in the public domain and, consequently, they cannot be used neither by Authorities or minor companies.

3.3. Recent efforts in Italy for updating Failure Rates

The mandatory periodical inspections of pressure equipment could provide a valuable source of information. Public control body are able to follow all step in pressure equipment lifecycle, production, commissioning, periodical verifications, repairs, decommissioning and demolition. Unfortunately most information is scattered throughout the local agencies and the regional authorities. A decade ago, a pioneer study was presented by the Region Emilia-Romagna, where the recorded anomalies were analyzed as verified by the public control body [18]. Featuring 46.000 pieces of equipment under observation and five years observation period, the study is significant indeed.

Since 2012 INAIL has been in charge to organize a data base of the verification activities for working equipment, including fired and unfired pressure vessels and pressure piping. This is a good chance indeed to organize the knowledge about pressure equipment life cycles, defects, anomalies and failures. the analysis of the knowledge potential of data gathered in the verification activities throughout Italy, which are in charge of INAIL. As a first experiment pressure equipment failures have been investigated in a single Italian Province. The Varese area has been selected as pilot-province, as it is featuring a wide range of different industries, with some 7500 pressure equipment in service. There are also 28 Seveso plants. The Varese Local Health Agency provided their pressure equipment failure sheets from 2003 to now. For each recorded event an adequate set of detailed information has been provided, including photographs. A further source of information is the Italian Association of LPG, which is used to collect data about failures of small sized LPG tanks. Data are trusted by National Fire Brigade. Of course small LPG tanks are very simple, highly standardized and mostly used for domestic or similar purpose, thus they are much more reliable than complex equipment, used in stressed environment.

3.4. More Knowledge is More Safety

The pilot study based on failures recorded in Varese area has been exploited also to define a grid to gather useful data, in order to extract knowledge about the modes of failure and above all to understand how main factors influence the frequency of failure, including type of construction material, type of equipment (according to usual PED classification), operation parameters, type of company organizational models (e.g. Seveso). The grid is divided in section about establishment, equipment, event, damages and consequences. A good grid is essential for a first understanding, but a lot of knowledge may be hidden in free text event description, as well as in detail photographs. For this purpose the potential of advanced Knowledge Based KB techniques will be exploited to extract empirical rules useful to drive the risk management in process plants, as discussed by Bragatto & al. [9].

4. Results

The results of the first pilot Surveys are presented and discussed in the present chapter.

4.1. Synopsis of "official" and "experimental" data

The data gathered by Italian authorities and association, as described in § 3.3, has been processed to have a first appraisal of failure rates, as reported in table 1.

Table 2 Failure Rates derived by failure frequencies, as recorded by Authorities and association.

	LPG association 2002-12	Em.Rom. 1993-2003	ASL Varese 2003-13
small	$3{,}35\ 10^{-6}$	$1{,}65\ 10^{-4}$	$1{,}33\ 10^{-4}$
large	$6{,}70\ 10^{-7}$	$5{,}28\ 10^{-5}$	$6{,}67\ 10^{-5}$
catastrofic	$3{,}35\ 10^{-7}$	$9{,}32\ 10^{-6}$	$1{,}33\ 10^{-5}$
equipment population	1,600,000	46,000	7,500

It has to be stressed that values for Italy are original elaborations of the authors, which processed basic data provided by control bodies or associations. The derived values has been compared with "historical values", as described in § 3.1 and with "official" European values, as described in §3.2. Figure 1 shows a graph featuring the Failure Rates for pressure equipment derived by Bush[8]; the values used in Canvey and Rijmond LUP studies , the values proposed by "official" or semi official sources (TNO, HSE, API, Aminal and, in the last three columns, the new Italian data. For uniformity of comparison were considered only failures with loss of containment. An attempt has be done to harmonize the discrimination of minor and major failures. In a few study it is based on the hole size, (e.g.< or > 10mm), whilst in other study the discrimination is based on repairability. The definition of "catastrophic" failure as it complete vessel destruction with consequent casualties, or severe damages for asset or environment. As catastrophic events are not so usual, in a few cases the available date are not statistically significant; in this case are shown in a lighter color.

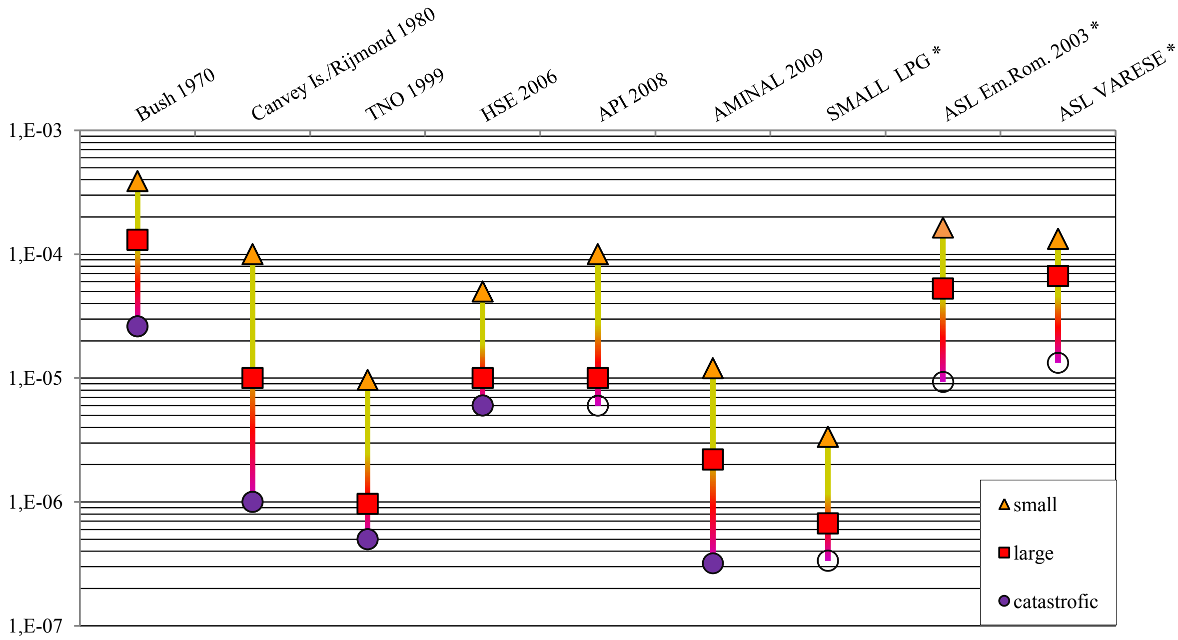

Fig. 1. The "Italian" failure rates are shown in right columns*, compared to public domain and historical sources.

4.2. Failure Modes

The grid mentioned in 3.4 has been experimented to gather data coming from Varese area. The data are not enough to provide significant and trustable data, anyway the distribution of the failure according the PED category and the type of failure, as shown in figure 2, may give a feeling of the potential of gathered data.

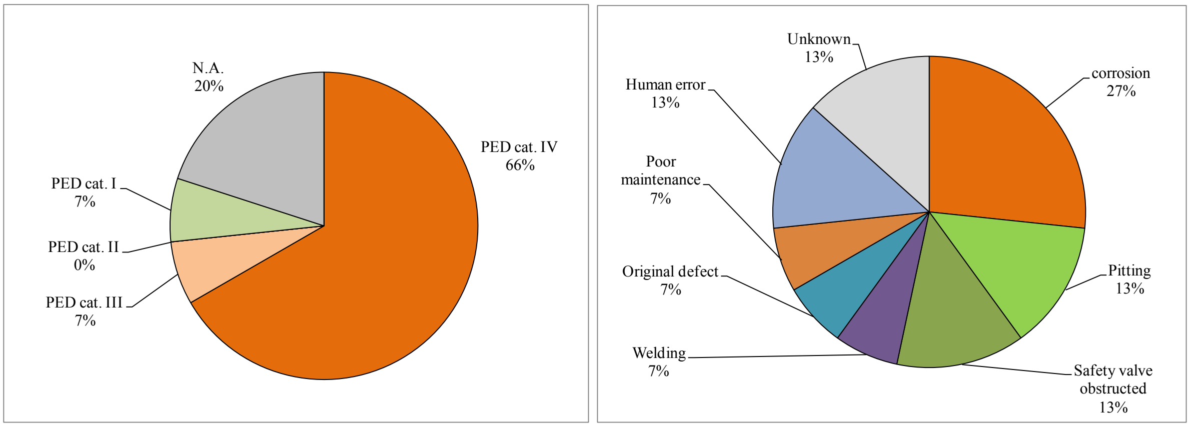

Figure 2 failed pressure equipment in Varese area: (a) PED category (b) Causes

4.3. Discussion

Pressure equipment Failure rates as evaluated in Varese and Emilia-Romagna areas are a bit lower of historical values of the Seventies; thus is confirmed the real improvement of pressure equipment reliability in the last decades, even though lower than supposed.

The experimental results are instead much higher than the "official" data proposed by Dutch and Flemish Authorities and even higher than API and HSE values. It has to be stressed that both in Varese and in Emilia-Romagna equipment in industrial and civil premises are not discriminated, whilst "official" and "historical" data are just for industrial sites, which have to be assumed more efficient in safety management. At the end API an HSE values, as quite conservative, are basically confirmed by experimental Italian data, whilst other data are too "optimistic" and inadequate for an application by Italian Authorities.

The Failure rates for LPG are instead, very low indeed, but it is a niche sector, featuring a very good industrial association, an adequate safety culture and highly standardized operation, thus they should be considered a model to achieve for other industries.

The very first results on failure modes confirm that "technical" issues are still the main cause of equipment failure, even though about one third of the failure is due to some human and organizational issue. Furthermore in the highest PED category, the failure rate seems much higher; that is not so strange due the more severe condition of service.

5. Conclusions

The failure rates are the cornerstone of the risk management; but unfortunately in the process industries the "historical" values are obsolete and could be misleading. The systematic collection of data on pressure vessels subject to mandatory verification, is a great opportunity to increase knowledge on the matter. An updated set of general failure frequencies for risk assessment and decision making, is urgent. The structured grids to collect information from the field is suitable to organize the inspector practical experience, which, otherwise, would be isolated and useless. The failure rules, managed by means of advanced KB techniques will be exploited to promote sound risk management procedures throughout the Italian Process Industries. At now the efforts are focused on pressure equipment, but in the future a similar road could be traced also for other type of equipment, such as lifting machines or atmospheric vessels.

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